BULLETIN No. 7. S. 9.

U. S. DEPARTMENT OF AGRICULTURE.

DIVISION OF SOILS.

AN ELECTRICAL METHOD

OF

DETERMINING THE TEMPERATURE OF SOILS.

BY

MILTON WHITNEY AND LYMAN J. BRIGGS.

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LETTER OF TRANSMITTAL.

UNITED STATES DEPARTMENT OF AGRICULTURE,
DIVISION OF SOILS,
Washington, D. C., March 11, 1897.

SIR: I have the honor to transmit herewith a description of an electrical method of determining the temperature of soils, and to recommend that it be published as Bulletin No. 7 of this Division.

Respectfully,

MILTON WHITNEY,
Chief of Division.

Hon. JAMES WILSON,
Secretary of Agriculture.

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INTRODUCTION.

Ever since the oft-quoted experiments of Schübler, on the relation of soils to heat, agricultural investigators have been more or less interested in soil temperatures. Periodic efforts have been made to study the relation of certain soils to heat and a considerable amount of material has been accumulated, but the results have been in the main very confusing and hard to interpret. This has been due to several causes. It will be remembered that Schübler worked with air-dry samples in the laboratory and found remarkable differences in the heat capacity and radiating power of sand, clay, and humus. His results have been very misleading as applied to field conditions, which are so different from the laboratory conditions of his experiments.

In the laboratory the dry sand quickly acquires a higher temperature from the same source of heat than the clay. In the field both soils are moist. The specific heat of water being eight times greater than soil, the same source of heat would only raise the temperature of a given weight of water one-eighth of the amount it would raise the temperature of an equal weight of soil. It is therefore apparent that the amount of moisture in the two soils would probably have more to do with the temperature of the field than the difference in the specific heat of the soils. Furthermore, the proportion of the moisture resulting from rains, which is evaporated from the surface, is transpired by plants, and percolates through the soil and runs off into streams, has a very material influence upon the temperature of a soil in the field. It is a complicated problem and one which can not be reasoned out nor settled in the laboratory, but can only be determined by field records.

Is the temperature of a light sandy truck land warmer or colder than that of a stiff clay wheat or grass land? This is the simplest, as well as the most important, of the fundamental problems to be settled. The next step would be to determine if the soil in which the roots of plants are hidden is warmer or colder on the average than the conditions under which the top of the plant is growing, and whether the difference, if there is any, is constant during all the growing period of the plant.

This brings up one very important point—that temperature observations in a single soil have comparatively little value. The real value of the work is only apparent when soils of different character and

different agricultural values are compared. Observations at a single depth in each of the soils of widely different character have far more value than observations at a dozen depths in the same soil. Engineers and physicists have studied the general relation of soils and rocks to heat sufficiently to establish the general laws of the periodic waves of heat which descend into the earth.

Numerous objections have been urged against the use of thermometers for taking the temperatures of soils. In the first place, the bulbs of soil thermometers are usually of an undetermined length, and as the temperature of the layers of soil are liable to vary greatly, even for very slight depths, it is difficult to know just what depth the thermometer represents, or rather it is difficult to have two thermometers represent the same depth. This has been corrected in some forms of thermometers by making the bulbs of some certain length, as 3 inches, 6 inches, and the like.

A more serious objection, however, to the ordinary form of soil thermometers is that when the bulb is more than a few inches below the surface of the ground, while the scale is above the surface, the effect of the great range of temperature near the surface on the long column of mercury in the stem is sufficient to very materially affect the result.

Where a number of thermometers at different depths in the same soil are read at the same time they will be at different parts of their daily range. Thus in North Carolina[1] it was found that the maximum temperature of the day occurred at the surface of the ground at 1 p. m.; 3 inches deep, 3 p. m.; 6 inches deep, 5 p. m.; 12 inches deep, after 7 p. m.; 24 inches deep, 7 a. m. Any observations made of the temperature at these various depths at the same moment of time might obviously be very misleading, and the results would in any case be hard to interpret.

The relative temperature of a soil is certainly one of its important physical properties, and it is important that this line of work be continued in order that some of the fundamental problems be solved. We should at least know the relative temperature of the soils adapted to our different agricultural interests.

In perfecting the electrical method for moisture determinations in soils, described in Bulletin No. 6 of this Division, a compensation cell, having the same electrical temperature coefficient as the soil is used as one arm of the Wheatstone bridge, in order to eliminate temperature effects in determining the electrical resistance of soils. Thermometers could not be used satisfactorily on account of the objections which have just been urged. Furthermore, the use of thermometers would necessitate the correction of all resistances to reduce them to a uniform temperature. This form of cell can very readily be used for taking the temperature of soils, and it obviates several of the instrumental defects of the ordinary soil thermometer.

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[1] Annual Report, N. C. Ex. Sta., 1886, p. 108.

The temperature cell consists essentially of a small glass tube nearly filled with a salt solution, with electrodes dipping into the salt solution at either end of the cell. The resistance is measured by the Wheatstone bridge method, an alternating current being employed to prevent polarization, with a telephone in place of the usual galvanometer. The resistance of the cell is more than twice as great at 32° as it is at 90° F., the resistance of electrolytes, unlike that of most metals, being higher at the lower temperature.

In order to use this cell for obtaining the temperature of a soil a simple salt solution may be used, but where the cells are to be used to eliminate the effect of variations in temperature, as in the method of moisture determinations described in Bulletin No. 6, the solution must have the same temperature coefficient as the soil, and as the cells are usually used for this double purpose it is preferable to use a solution having the same temperature coefficient as the soil.

THE TEMPERATURE-RESISTANCE COEFFICIENT OF SOILS.

In order to determine the temperature coefficient of soils, a small quantity of soil is put into a cell and regularly standardized at different temperatures. These cells are constructed of strips of glass cemented together with marine glue. They are 3 inches long, 2 inches wide, and one-half inch thick in external dimensions. The electrodes consist of two carbon strips one-half inch wide and 3 inches long, copper plated on one end. Insulated copper wires are soldered to the electrodes. The electrodes are then cemented to the glass strips forming the narrow sides of the cell, and are then filed down until only a thin strip of carbon remains. The cell is then put together by means of marine glue, with the carbon electrodes facing each other. The soil to be tested is mixed with distilled water to bring it to a condition about suitable for potting plants. A quantity of the moist soil is then firmly packed into the cell. It is advisable to add a drop or two of carbolic acid to prevent organic changes in the soil. A strip of glass is then put over the top and fastened with marine glue. The wires leading from the electrodes should be firmly attached to the outer side of the cell, to prevent injury in handling to the insulation where the wires enter the cell. The cell as thus prepared must be impervious to water, and to insure this it is well to cover it, after filling, with a second coating of marine glue.

These earth cells are then standardized at various temperatures in the same way as the glass temperature cells, which will be shortly described.

Owing to the difference in resistance of the cells, due to difference in the salt content, and the difficulty of packing the soils uniformly, the resistances of different cells can not readily be compared until they are reduced to a common standard. For this reason the resistance of each cell is so reduced as to make the resistance at 60° F. equal 1,000. This

gives a ratio of change of resistance with temperature by which all cells can be readily and accurately compared. The reduction is easily made. If at 60° a cell has a resistance of 1,600 ohms all of the observed resistances of this cell should be multiplied by 1,000/1,600. If the observed resistance at 60° is 900 ohms all of the other resistances of this cell should be multiplied by 1,000/900.

The following table gives the temperature coefficient as determined from twenty-seven cells of nine typical soils of the United States:

Temperature coefficient of nine types of soil.

Kind of soil.	Locality.	32°	35°	40°	45°	50°	55°	60°	65°	70°	75°	80°	85°	90°
Red hill	South Carolina	1,638	1,527	1,382	1,265	1,162	1,076	1,000	933	869	811	758	709	664
Limestone clay*	Virginia	1,618	1,511	1,370	1,257	1,157	1,074	1,000	935	877	823	773	727	685
Gabbro	Maryland	1,613	1,507	1,366	1,254	1,156	1,073	1,000	935	874	819	767	720	677
Alkali	Colorado	1,609	1,504	1,365	1,253	1,155	1,073	1,000	935	874	818	767	719	673
Adobe	New Mexico	1,602	1,498	1,360	1,250	1,153	1,072	1,000	937	876	822	772	725	683
Loam	Maryland	1,595	1,492	1,356	1,247	1,151	1,071	1,000	938	878	824	775	729	687
Export tobacco†	Kentucky	1,590	1,488	1,353	1,245	1,150	1,071	1,000	937	876	822	772	725	683
Truck	Maryland	1,586	1,482	1,351	1,244	1,149	1,070	1,000	940	882	830	782	738	697
Loess	Illinois	1,576	1,476	1,345	1,240	1,147	1,069	1,000	936	875	821	770	724	681
Mean		1,601	1,497	1,360	1,250	1,153	1,072	1,000	937	877	823	773	727	685

* Trenton limestone. † Subcarboniferous.

These soils represent some of the extreme types found in the United States, so far as the texture and chemical composition are concerned. At either end of the range of temperature, where the differences between the soil resistances are greatest, the mean probable error of using any one of these soils as standards, compared with the mean of all, is $\pm$ 1.2 per cent at 32°, while at 90° it is $\pm$ 1.4 per cent.

GLASS TEMPERATURE CELLS.

It was found that a simple solution of pure sodium chloride in distilled water does not have quite as great a temperature coefficient as the mean coefficient of these nine types of soil. It was found, however, that by the addition of alcohol the coefficient could be very materially changed, and in this way it was possible to make a temperature cell having a temperature coefficient practically equal to the mean coefficient of these nine types of soil.

The cell is made of a small glass tube about 3.5 millimeters in internal diameter, with platinum electrodes fused into each end, the cell being nearly filled with a salt solution. The electrodes are made of No. 25 platinum wire, twisted at one end to flat spirals which are parallel to each other and three inches apart. To prevent polarization, and to increase the sharpness of the minimum in the telephone, the spirals are covered with a coating of platinum black. The plating is done by passing a current of three or four volts E. M. F. through a solution of 1 part of platinic chloride and 0.008 part of lead acetate in 30 parts of water, using the platinum spiral as a negative electrode.

The salt solution in the cell covers both electrodes, and extends 4 or 5 millimeters above the upper one. Above the surface of the liquid there is an air space about 1 centimeter long to allow for the expansion and contraction of the solution. The salt solution finally adopted for use in the temperature cells contains 90 per cent of four-fifths normal pure sodium chloride solution and 10 per cent of commercial alcohol. Insulated, flexible wires are soldered to the electrodes at either end of the cells when they are ready to be standardized for use. When a fresh lot of solution has been used in the construction of a lot of new cells, several cells should be standardized at different temperatures in order to be certain that the solution has the proper temperature coefficient. If this is known to be correct, then the cells need only be standardized at a single temperature, from which the resistances of all other temperatures can be readily calculated.

In order to standardize the cells they are packed in pounded ice, in which they are kept at least half an hour after the resistance appears to be constant. The lead wires and ends of the electrodes going out from the cells must be thoroughly insulated, so that all of the current passes through the cell. The resistance of each cell is taken at least four or six times during this period to be sure that it is constant. This gives the resistance at 32° F. The cells are then placed in a large volume of water, or of linseed oil, at 40° F., and kept at that temperature for at least half an hour after the resistance of the cells appears to be constant. It is well to have the water or oil in a tin pail placed inside a large tub containing water. In this way the temperature can be maintained constant to within 0.1 or 0.2° C. by constant stirring and the addition of small quantities of either warm or cold water or oil. After the resistance of each of the cells has been taken a number of times at this temperature, the temperature of the bath is raised ten degrees Fahrenheit and the process repeated until the cells are standardized at every ten degrees between 32° and 100° F.

These cells have the great advantage that they can be easily and cheaply constructed in the laboratory and of any size desired. Cells have been used in this Division with the electrodes 1 inch, 3 inches, and 6 inches apart. For some special investigations in greenhouse soils cells were made with the electrodes 3 feet apart. In all such cases the diameter of the tube and the concentration of the solution should be so adjusted that the resistance of the cell will be about 2,000 ohms at 60° F. Considerable variation will occur, however, and each cell must be standardized at at least one temperature before being put into the soil.

The following tables give the actual resistance and the relative change of resistance of 6 temperature cells with temperature, selected at random from a lot which were made for this Division. The mean resistance of 21 of these cells for each 10 degrees in temperature was plotted and a smooth curve drawn through the points. From this curve, which is given in the accompanying figure, the resistance for

each degree between 32° and 100° F. was determined, and is given in the first column of the table for calibrating temperature cells.

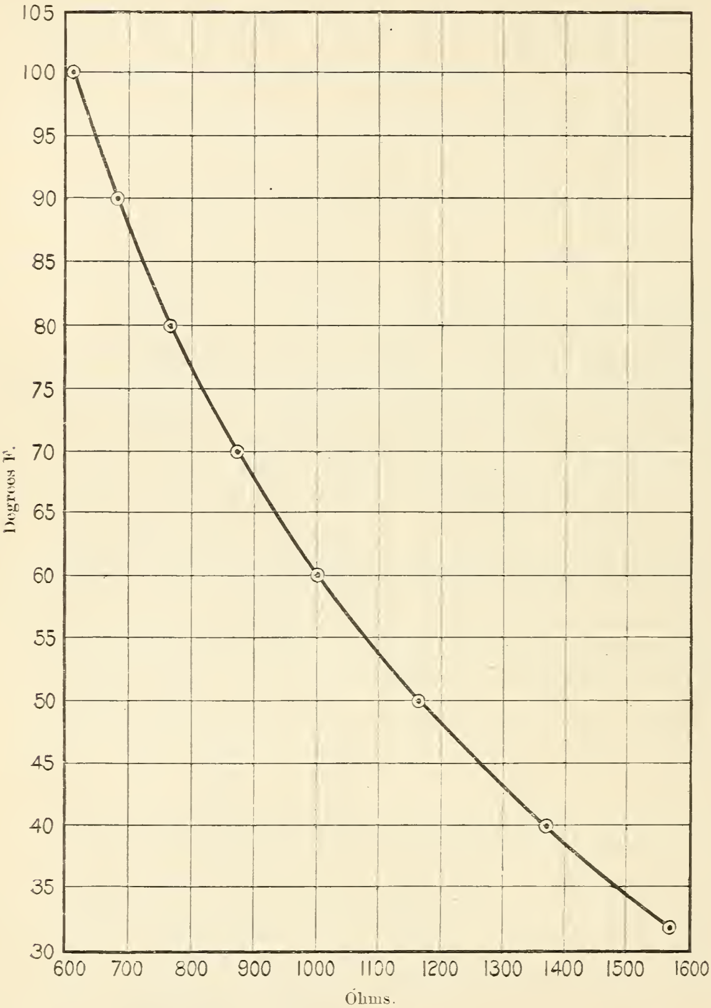

FIG. 1.—Relative change of resistance of a temperature cell with temperature.

Actual resistance of six temperature cells at different temperatures.

Cell No.	32°	40°	50°	60°	70°	80°	90°	100°
140	3,030	2,661	2,257	1,944	1,695	1,494	1,328	1,192
141	2,750	2,410	2,045	1,762	1,536	1,354	1,202	1,078
142	3,240	2,830	2,400	2,068	1,801	1,589	1,412	1,268
143	3,264	2,857	2,426	2,087	1,819	1,604	1,427	1,281
144	3,384	2,965	2,512	2,166	1,883	1,659	1,474	1,321
145	2,736	2,393	2,030	1,747	1,524	1,341	1,191	1,066

Relative resistances of six temperature cells at different temperatures.

Cell No.	32°	40°	50°	60°	70°	80°	90°	100°
140	1,559	1,369	1,161	1,000	872	769	683	613
141	1,561	1,368	1,161	1,000	871	768	682	612
142	1,566	1,369	1,161	1,000	871	768	683	613
143	1,563	1,369	1,162	1,000	871	768	683	614
144	1,563	1,369	1,160	1,000	869	766	680	610
145	1,562	1,371	1,162	1,000	872	768	682	611

The mean rate of change of resistance with temperature of twenty-one cells was found to be practically the same as the mean temperature coefficient of the nine types of soils already mentioned.

In order to construct correction cards for temperature calls a table has been prepared to facilitate the work. The first column of the table contains the mean rate of change of resistances with temperature, the resistance at 60° being taken to equal 1,000. The other columns are multiples of this. In order to construct a correction card for any cell by the use of this table the resistance of the cell at 60° F. should be known. If it can not conveniently be standardized at 60°, the reading at any other temperature can readily be reduced to the temperature of 60° by dividing the observed resistance by the resistance for that temperature in the first column of the table and multiplying the quotient by 1,000. For example, if the cell has a resistance of 1,913 ohms at 70°, the resistance at 60° will be $\frac{1{,}913}{870}1{,}000=2{,}197$ ohms. Having the resistance of the cell at 60°, the resistance at any other temperature can be readily determined from the table.

If the cell has a resistance of 2,197 ohms at 60°, the resistance at 40° would be found as follows: It will be noticed that 2,000 ohms at 60° is equal to 2,738 ohms at 40°. 1,000 ohms at 60° is equal to 1,369 ohms at 40°. 100 ohms would be one-tenth of this. The separate values are therefore found and added in the following way:

$$
\begin{aligned}
2{,}000 &= 2{,}738 \\
100 &= 137 \\
90 &= 123 \\
7 &= 9 \\
\hline
2{,}197 &= 3{,}007 \text{ at } 40^\circ \text{ F.}
\end{aligned}
$$

Table for calibrating temperature cells.

°F.	1,000.	2,000.	3,000.	4,000.	5,000.	6,000.	7,000.	8,000.	9,000.
32	1,564	3,128	4,692	6,256	7,820	9,384	10,948	12,512	14,076
33	1,538	3,076	4,614	6,152	7,690	9,228	10,766	12,304	13,842
34	1,512	3,024	4,536	6,048	7,560	9,072	10,584	12,096	13,608
35	1,487	2,974	4,461	5,948	7,435	8,922	10,409	11,896	13,383
36	1,463	2,926	4,389	5,852	7,315	8,778	10,241	11,704	13,167
37	1,439	2,878	4,317	5,756	7,195	8,634	10,073	11,512	12,951
38	1,415	2,830	4,245	5,660	7,075	8,490	9,905	11,320	12,735
39	1,392	2,784	4,176	5,568	6,960	8,352	9,744	11,136	12,528
40	1,369	2,738	4,107	5,476	6,845	8,214	9,583	10,952	12,321
41	1,346	2,692	4,038	5,384	6,730	8,076	9,422	10,768	12,114
42	1,323	2,646	3,969	5,292	6,615	7,938	9,261	10,584	11,907
43	1,301	2,602	3,903	5,204	6,505	7,806	9,107	10,408	11,709
44	1,279	2,558	3,837	5,116	6,395	7,674	8,953	10,232	11,511
45	1,258	2,516	3,774	5,032	6,290	7,548	8,806	10,064	11,322
46	1,237	2,474	3,711	4,948	6,185	7,422	8,659	9,896	11,133
47	1,217	2,434	3,651	4,868	6,085	7,302	8,519	9,736	10,953
48	1,198	2,396	3,594	4,792	5,990	7,188	8,386	9,584	10,782
49	1,179	2,358	3,537	4,716	5,895	7,074	8,253	9,432	10,611
50	1,161	2,322	3,483	4,644	5,805	6,966	8,127	9,288	10,449
51	1,143	2,286	3,429	4,572	5,715	6,858	8,001	9,144	10,287
52	1,126	2,252	3,378	4,504	5,630	6,756	7,882	9,008	10,134
53	1,109	2,218	3,327	4,436	5,545	6,654	7,763	8,872	9,981
54	1,092	2,184	3,276	4,368	5,460	6,552	7,644	8,736	9,828
55	1,076	2,152	3,228	4,304	5,380	6,456	7,532	8,608	9,684
56	1,060	2,120	3,180	4,240	5,300	6,360	7,420	8,480	9,540
57	1,045	2,090	3,135	4,180	5,225	6,270	7,315	8,360	9,405
58	1,030	2,060	3,090	4,120	5,150	6,180	7,210	8,240	9,270
59	1,015	2,030	3,045	4,060	5,075	6,090	7,105	8,120	9,135
60	1,000	2,000	3,000	4,000	5,000	6,000	7,000	8,000	9,000
61	986	1,972	2,958	3,944	4,930	5,916	6,902	7,888	8,874
62	972	1,944	2,916	3,888	4,860	5,832	6,804	7,776	8,748
63	958	1,916	2,874	3,832	4,790	5,748	6,706	7,664	8,622
64	944	1,888	2,832	3,776	4,720	5,664	6,608	7,552	8,496
65	931	1,862	2,793	3,724	4,655	5,586	6,517	7,448	8,379
66	918	1,836	2,754	3,672	4,590	5,508	6,426	7,344	8,262
67	906	1,812	2,718	3,624	4,530	5,436	6,342	7,248	8,154
68	894	1,788	2,682	3,576	4,470	5,364	6,258	7,152	8,046
69	882	1,764	2,646	3,528	4,410	5,292	6,174	7,056	7,938
70	870	1,740	2,610	3,480	4,350	5,220	6,090	6,960	7,830
71	859	1,718	2,577	3,436	4,295	5,154	6,013	6,872	7,731
72	848	1,696	2,544	3,392	4,240	5,088	5,936	6,784	7,632
73	837	1,674	2,511	3,348	4,185	5,022	5,859	6,696	7,533
74	826	1,652	2,478	3,304	4,130	4,956	5,782	6,608	7,434
75	816	1,632	2,448	3,264	4,080	4,896	5,712	6,528	7,344
76	806	1,612	2,418	3,224	4,030	4,836	5,642	6,448	7,256
77	796	1,592	2,388	3,184	3,980	4,776	5,572	6,368	7,164
78	786	1,572	2,358	3,144	3,930	4,716	5,502	6,288	7,074
79	776	1,552	2,328	3,104	3,880	4,756	5,432	6,208	6,984
80	767	1,534	2,301	3,068	3,835	4,602	5,369	6,136	6,903
81	758	1,516	2,274	3,032	3,790	4,548	5,306	6,064	6,822
82	749	1,498	2,247	2,996	3,745	4,494	5,243	5,992	6,741
83	740	1,480	2,220	2,960	3,700	4,440	5,180	5,920	6,660
84	731	1,462	2,193	2,924	3,655	4,386	5,117	5,848	6,579
85	722	1,444	2,166	2,888	3,610	4,332	5,054	5,776	6,498
86	713	1,426	2,139	2,852	3,565	4,278	4,991	5,704	6,417
87	705	1,410	2,115	2,820	3,525	4,230	4,935	5,640	6,345
88	697	1,394	2,091	2,788	3,485	4,182	4,879	5,576	6,273
89	689	1,378	2,067	2,756	3,445	4,134	4,823	5,512	6,201
90	681	1,362	2,043	2,724	3,405	4,086	4,767	5,448	6,129
91	673	1,346	2,019	2,692	3,365	4,038	4,711	5,384	6,057
92	665	1,330	1,995	2,660	3,325	3,990	4,655	5,320	5,985
93	658	1,316	1,974	2,632	3,290	3,948	4,606	5,264	5,922
94	651	1,302	1,953	2,604	3,255	3,906	4,557	5,208	5,859
95	644	1,288	1,932	2,576	3,220	3,864	4,508	5,152	5,796
96	637	1,274	1,911	2,548	3,185	3,822	4,459	5,096	5,733
97	630	1,260	1,890	2,520	3,150	3,780	4,410	5,040	5,670
98	623	1,246	1,869	2,492	3,115	3,738	4,361	4,984	5,607
99	617	1,234	1,851	2,468	3,085	3,702	4,319	4,936	5,553
100	611	1,222	1,833	2,444	3,055	3,666	4,277	4,888	5,499

MEASURING THE ELECTRICAL RESISTANCE OF TEMPERATURE CELLS.

The electrical resistance of the cells can readily be measured by a slide meter bridge or box of coils found in nearly all physical and chemical laboratories, or which can readily be constructed, using the alternating current from a small induction coil, with a telephone in place of the galvanometer. The cells were, however, designed for and are very conveniently measured by the portable bridge box described in Bulletin No. 6 of this Division. This consists essentially of a rheostat, comparison coils and induction coil, and a watch-receiver telephone. One arm of the bridge contains a 1,000-ohm comparison coil, a second arm contains a 900-ohm coil and a 100-ohm coil in series, while a third arm contains the rheostat. The rheostat contains 102 10-ohm coils, while 4 1,000-ohm coils can be successively thrown in in series with the rheostat so that the resistances can be varied from 0 to 5,020 ohms. By means of a switch the 900-ohm comparison coil of the second arm of the bridge can be short-circuited so as to increase the range of the box tenfold. The wires from the temperature cell, buried in the soil at any distance from the observer, are connected to the proper binding posts and form the fourth arm of the bridge. More detailed instructions in regard to the construction and use of the bridge box may be obtained by consulting Bulletin No. 6 of this Division.

BURYING THE TEMPERATURE CELLS IN THE SOIL.

The cells may be buried in an excavation in the field to the proper depth and covered. It is better, however, to mount them on wooden blocks, lower the blocks to the proper depths in an auger hole, wedge them up so as to bed the cells in the soil and fill the hole with melted pitch.

The cells may be placed in an upright position in the soil and the temperature integrated for a depth corresponding to their own length, or they may be placed horizontally, when they will give the temperature of a depth corresponding to the thickness of the tube. They can be buried at any depth in the soil and remain there throughout the season, or they may be hung far up in a tree, or folded in a leaf, or attached to a stalk to get the temperature of a plant. It may be a mile away from the observing station. The only thing essential is that the resistance of the wires be negligible compared with the resistance of the cell.

For ordinary work it is best to have the resistance of the cell about 2,000 ohms at 60° F. Such a cell will vary 30 ohms in resistance between 59° and 60° F. If it has twice the resistance the variation will be twice as great.

The resistance of even a considerable length of wire may be rendered negligible by increasing the resistance in the cell. It is also possible to increase the sensitiveness of the cell by increasing the resistance.